Filter Concepts for Gas Turbines – Overview and Field Report on Utility Value Enhancement with Three-stage Filtration

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Filterkonzepte für Gasturbinen – Übersicht und Praxisbericht zur Nutzwertherhöhung mit dreistufiger Filtration


Erfahrungen aus implementierten mehrstufigen Systemen belegen die Anwendbarkeit auf die derzeit gängigen statisch betriebenen Filtersysteme vor dem Hintergrund der Forderungen nach Partikelabscheidung, Koaleszenzvermögen und Druckverlustverhalten. Zwar bilden mehrstufige Systeme den Nachteil eines anfänglich höheren Druckverlusts, ermöglichen durch fast vollständig vermiedene Verschmutzung und erhöhte Anlagenverfügbarkeit einen deutlichen, belegbaren Kostenvorteil.


Introduction

Responsible deployment of the fossil resources at our disposal demands their maximally efficient and eco-neutral use while simultaneously factoring in their cost-efficient utilisation. To reconcile both these aspects is the paramount goal governing the development efforts of turbine manufacturers, system development engineers and system operators alike.

From a system operator’s viewpoint, it is primarily downtimes that are rated as lost profit, and must therefore be avoided. High levels of availability and long running times for the systems concerned are the declared goals. In particular, downtimes required for washing the compressor stages inevitably cause nonproductive periods, which need to be minimised or altogether avoided. The aim of the washing routines is to remove any coatings and deposits on the blading. The cause for any such deposits will usually be inadequate intake air filtration. Innovative concepts for enhancing filtration quality by means of three-stage filter systems were presented in [1].

This paper provides an overview of filter systems in current use and an approach for estimating the financial benefits accruing from system modification, an approach which is illustrated by examples from actual operational practice.

Principles of Particle Filtration

The demand for efficient air filtration for internal combustion engines entails sophisticated challenges in terms of adequate design for and implementation of the air intake systems being used.

An air filter system is required to significantly reduce the penetration of solid and liquid particles into the turbomachinery, while coping with temporally fluctuating environmental conditions.

Capturing of air-borne particles (which may be dust particles or droplets) depends most particularly on the transport mechanisms effective at the location concerned. Electrostatic, diffusion-, inertia-, and gravity-related effects are responsible for particle transport to the filter media, which are usually made of fibres. The adhesion forces operating between particles and fibres in their turn are determined by the interaction of Van der Waals forces, and electrostatic and liquid-related effects, and enable dirt particles to be permanently arrested. When developing filter elements, then, both these mechanisms, the transport and the adhesion mechanism, must be given due consideration in the optimisation process.

The concentration of air-borne dust particles is of crucial importance for the design of intake air filtration systems. Over the past few years, measurements of dust concentrations have been continuously expanded, so now there is a broad data base available [2]. The temporal fluctuation band of the PM10 dust mass found here ranged from approximately 5 to 40 µg/m³ [3] in Germany during 2007, and depends largely on the season of the year, on the surrounding landscape and the degree of industrialisation obtaining at the place where the measurements are taken. In this context, PM10 denotes the dust fraction whose mean particle size (aerodynamic equivalent diameter) is 10 µm, with 50% of it being arrested. This dust fraction exhibits a particle size distribution that may well contain particles of up to 20 to 30 µm in diameter [4].

The fact that a very high and nonetheless limited proportion of the dust fraction is being retained also means that there will always be particles penetrating the filter. As a consequence of particles passing through a filter stage, deposits are formed on the blading, which results in output losses at the gas turbine. In regions close to the coast, additional corrosion effects may be encountered, due to air-borne salt particles. The aim of development work on filter systems is accordingly to minimise precisely that proportion of the dust fraction which passes through the filter. Filtration quality is rated in terms of collection efficiencies for individual particle sizes or for the entire dust quantity in question [5].

Filtration Concepts for GT Applications

The temporal dust mass carried in determines the choice of a suitable intake air filter sys-
tem. The size of the particles of relevance for intake air filtration is typically to be found in a bandwidth of around 0.01 µm to about 3 mm, and at locations exposed to high industrial emissions an average mass concentration of up to 200 µg/m³ can occur [6].

It is only in a few regions (exposed to temporarily extra-high dust concentrations) that re-generatively operated systems are actually necessary, which, following the principle of surface filtration, form a compact dust cake on the filter medium involved. Using the pulse-jet cleaning method, the dust cake can subsequently be shaken off the filter medium at pre-defined intervals. Filter systems of this kind are mostly in single-stage design and require precisely harmonised and properly functioning cleaning systems. The drawback with these is a relatively high degree of particle penetration during and shortly after the cleaning phase, since it is precisely then that the filtration-supporting effect of the dust cake is absent; it will only be built up again over the course of the cycle now commencing.

In most of the Earth’s regions, low to moderately dust masses are encountered, which can be very successfully stored and lasting retained in the element’s filter medium using the principle of deep-bed filtration. If the dust-retention capacity is exhausted, the filters concerned are replaced by new, non-loaded elements during the system’s overhaul and standby times. The salient features of static filtration systems are these: arrestance of large particles in a pre-filter stage and storage of small particles in the fine-filter stage. Static air filter systems of this kind can be supplied in multi-stage design, which offers scope for optimizing the filter technology involved.

The task of a state-of-the-art design for intake air filters is to affordably reconcile the paramount requirements posed for optimum system operation:

- Maximised system protection = filtration with maximum efficiency and at a consistently high level
- High system availability = downtimes for replacing the filters are rare and short
- High system efficiency = low pressure drop in the filter system
- Reduction in unplanned downtimes of the filter system = failsafe product quality

Figure 1 illustrates the basic set-up of a two-stage filter system, in which the final cassette filter stage is protected by an upstream pocket filter stage. The core for top-quality filtration of a three-stage filter system as depicted in Figure 2 is the high-efficiency particulate air (HEPA) filter (Filter Class H11 as defined in EN1822) installed in the third filter stage. The upstream filter stages serve primarily to protect the HEPA filter in the final filter stage. The task of pre-filtration is frequently handled by a pocket filter of Filter Class F6 (as defined in EN 779), which in its turn is installed upstream of the intermediate stage comprising F8 or F9 cassette filters. Which filters to choose for these two stages depends crucially on the environmental conditions concerned and the building constraints encountered.

A reduction in the number of pre-filter stages or of the Filter Class will directly affect the dust volume passing through the filter stages concerned, and thus the useful lifetime achievable for the HEPA filter in the final filter stage. Moreover, possible effects exerted by the ambient air’s humidity in conjunction with the dust arrested in the filter stages must be given due consideration, particularly when swellable or sticky dust constituents are involved. These might be responsible for an unforeseeable rise in the pressure drop as a consequence of weather-related factors. Another task to be performed by the upstream filters is to act as coalescence stages. Minute droplets of fog contained in the intake air condensate at the fine fibres of the pre-filters and coalesce. Gradually, these droplets reach a flowable state, and driven by gravity flow down so that they may exit at the filter’s base. When the intake air is humidified by means of evaporation coolers, the effects described are encountered even more often, and must be given particular attention in the run-up to filter system dimensioning. In this case, it is absolutely imperative to use a two-stage pre-filter system, in which droplets are arrested to a sufficiently degree in the first filter stage so as to prevent the final HEPA filter stage being soaked through. Tests are also currently ongoing with filter systems comprising merely two filter stages at locations where only low humidity levels can be anticipated. Here, F7 pocket filters are used in the pre-filter stage upstream of the high-efficiency particulate air (HEPA) cassette filters of Filter Class H11. So far, however, the application results of these tests are not yet available. Of course, protection of the gas turbine is here assured to the same degree as in systems featuring two pre-filter stages. The results on the useful lifetime for the final HEPA filter are being eagerly awaited.

![Figure 1. Two-stage filter system comprising pocket and cassette filters.](image1)

![Figure 2. Three-stage filter system.](image2)

![Figure 3. Output loss due to compressor fouling and output recovery through “washing” in a two-stage filter system.](image3)
The principal focus of the considerations described in the previous publication was on two parameters, exhibiting both advantages and disadvantages [1].

The advantage offered by upgraded filtration is less fouling on the compressor section of the gas turbine.

In this context, the values compiled in Table 1 illustrate the improvement in arrerstance achieved by the three-stage HEPA filter system as compared to a conventional two-stage fine-filter system. When a HEPA filter system is used, the number of particles responsible for compressor fouling in sizes ranging from 0.3 to 0.5 µm can be reduced by a further factor of about 30, and the somewhat larger fraction of 0.5 to 1.0 µm in size by a factor of roughly 200.

The result of the empirical feedback so far obtained from the markets confirms these basic considerations. By using upgraded filtration technology featuring HEPA filters, the fouling customarily encountered on the compressor blading is avoided almost entirely. Feedback likewise confirms that online and offline washing can be completely dispensed with, creating the concomitant benefit that there is no longer any reduction in performance between one washing routine and the next (otherwise an accepted fact), which in turn shows up immediately as enhanced performance figures at the machine itself. What is more, non-productive times, reduced output levels and fouling entrainment as side-effects of the washing routines are a thing of the past.

In the theoretical deliberations of Schroth et al., a lower output loss of the three-stage system was taken into account, which is outlined as an example in Figure 3. The output loss has not materialized in actual practice. There is no particle penetration worth mentioning. Deposits on the turbine blading are being prevented almost entirely.

Figure 4 shows the endoscopic image of the compressor blading's surface in a Taurus 65 GT. After having been in operation for approx. 9,000 hours without any washing routine at all, no deposits whatsoever adhering to the blading are visible. This is an unequivocal success for the three-stage HEPA filter system featuring the combination F6-F9-H11.

The disadvantage of a three-stage filter system is, quite naturally (due to the contribution made by the third high-efficiency filter stage), the higher pressure drop that must be anticipated in the filter system as a whole.

In Figure 5, a pressure drop curve typical for a three-stage filter system is compared to that of a two-stage system. Here, the hatched area marks the difference and/or increase of the pressure drop over the entire operating period and thus provides a benchmark for the mechanical energy yield actually achieved.

As experience has shown, the output loss of a gas turbine due to a higher pressure drop in the intake system can be estimated at about 0.1 % efficiency loss for each 50 Pa of increase in pressure drop, and the direct effects of an additional third filter stage can be evaluated. In the analytical summary, the advantage of increased machine availability must at the very least compensate for the deleterious contribution of a higher pressure drop in the system, or even exceed it.

Typical Computation for a System

With an empirically based computation program, it is possible to use the operator's particulars on the status of the existing system to compare it with the modified, three-stage filter system, and to analyze the advantages and disadvantages involved.

The particulars required from the operator are the following (here reproduced as an example; Table 2).

Further particulars given for the existing filter system serve to provide a comprehensive overview of the application task involved and are factored into the computation if necessary.

Based on the operator’s particulars and the typical pressure-drop curves, on which the computation is based, the anticipated average pressure drops are estimated as a characteristic mean value over the entire period of operation for the individual filter stages. The results have been compiled in Table 3 and then compared with the values for the existing system.

Table 2. Typical particulars serving as the computation basis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum power output</td>
<td>31 MW</td>
</tr>
<tr>
<td>Operating hours per year</td>
<td>5,600 h/a</td>
</tr>
<tr>
<td>Approx. volume flow at 20 °C</td>
<td>231,126 m³/h</td>
</tr>
<tr>
<td>Number of filter elements per filter stage</td>
<td>63 pcs</td>
</tr>
<tr>
<td>Loss due to fouling in 40 days</td>
<td>700 kW</td>
</tr>
<tr>
<td>Volume flow loading per filter</td>
<td>3,700 m³/h per filter</td>
</tr>
</tbody>
</table>

Table 3. Computations for the two-stage system used.

<table>
<thead>
<tr>
<th>Filter Stage</th>
<th>Δp_Start [Pa]</th>
<th>Δp_End [Pa]</th>
<th>Characteristic mean value for pressure drop [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current filter system:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st stage</td>
<td>Pocket filter F6</td>
<td>70</td>
<td>250</td>
</tr>
<tr>
<td>2nd stage</td>
<td>Cassette filter F8</td>
<td>120</td>
<td>400</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>190</td>
<td>650</td>
</tr>
</tbody>
</table>
In this comparison, the difference between the characteristic mean values produces an anticipated pressure-drop increase of $493 \text{ Pa} - 343 \text{ Pa} = 150 \text{ Pa}$ for the three-stage filter system.

Output Loss Due to Fouling up to Turbine Washing in the Previous Filter System

Figure 3 shows an output curve typical for gas-turbine operation with washing routines, in the shape of a classical saw tooth curve. The output loss caused by fouling during the load period can be partly recovered by the washing routine. In a rough approximation, the hatched area below the curve can be regarded as a triangle and its area adduced as a dimension for the output loss involved.

To start with, the output loss due to a higher initial pressure drop in the three-stage filter system is estimated. This is obtained as:

$$P_{\text{GT,3-stage}_i} = P_{\text{GT}_i} \cdot C_{\text{DP,50Pa}} \cdot \frac{\text{DP}_{3-stage}_i}{50 \text{ Pa}}$$

where:

- $P_{\text{GT,3-stage}_i}$: Initial output loss of gas turbine in three-stage filtration system
- $P_{\text{GT}_i}$: Gas turbine's rating
- $C_{\text{DP,50Pa}}$: Efficiency loss coefficient
- $\text{DP}_{3-stage}_i$: Initial pressure drop in the three-stage filter system

With the typical values, the gas turbine's unavoidable output loss due to the higher initial pressure drop in the three-stage filter systems is obtained as:

$$P_{\text{GT,3-stage}_i} = 31 \text{ MW} \cdot 0.001 \cdot \frac{150 \text{ Pa}/50 \text{ Pa}}{0.093 \text{ MW}} = 0.093 \text{ MW}$$

The gas turbine’s output loss caused by the three-stage filter system within the period under review is calculated as:

$$P_{\text{Loss due to 3-stage filter system}} = P_{\text{GT,3-stage}_i} \cdot \text{operating period in hours}$$

$$P_{\text{Loss due to 3-stage filter system}} = 0.093 \text{ MW} \cdot 5,600 \text{ h} = 520.8 \text{ MWh}$$
Evaluation and Discussion of the Results

Due to cyclically occurring fouling, the gas turbine operated with the conventional two-stage filter system and regular washing routines loses approx. 1,300 MWh within the period under review. Taking an assumed remuneration for electricity of 65 €/MWh, this corresponds to a financial loss of around 84,900 €. This loss can be avoided by installing a three-stage filter system and profitably eliminated.

On the one hand, installation of a three-stage filter system increases the pressure drop, which in our example corresponds to an output loss for the gas turbine of approx. 520 MWh or a financial loss of around 33,800 €. On the other hand, this investment eliminates the two-stage system’s output loss, which was hitherto unavoidable.

Avoiding the costs caused by compressor fouling, of: = + 84,900 €

Accepting the additional costs incurred by a higher pressure drop: = − 33,800 €

Within the period under review, a total cost advantage of = + 51,100 € is thus obtained.

An estimate, plus a cost comparison, must be performed individually for each system in question. Note that further deleterious aspects have not yet been taken into account here, particularly the irreversible degradation of the gas turbine due to fouling. In spite of regular washing routines, the original performance level is impossible to reach again. With three-stage filtration, this effect is almost entirely avoided. Nor have the costs for cleaning agents and their disposal been factored into this computation. Effects improving the overall result, such as its no longer being necessary to add to the running time equivalent operating hours for the start-up procedures required after washing, and the increase in the gas turbine’s availability levels, have likewise not yet been factored in.

Typical Examples

The innovative filter concepts with upgraded filtration quality have been undergoing applications-engineering trials since 2003, and currently comprise more than 30 intake air systems from all front-ranking gas turbine manufacturers. One representative example each for a three-stage filter system (Figure 6) and the continuation of a two-stage high-performance system (Figure 7, 8) with a final HEPA filter stage are adduced here to demonstrate the expectations posed for the relevant performance capabilities.

Typical Example of Three-stage Filtration in HEPA Quality

System type 2 x Taurus 65 GT
Place of installation Cardboard factory
Systems rated at 6.3 MW
Total volume flow
per system 67,000 m³/h
1st filter stage 28 x F6 pocket filter T60
2nd filter stage 28 x F9 MaxiPleat MX 98
3rd filter stage 28 x H11 MaxiPleat MX100

Avoiding the costs caused by compressor fouling, of: = + 84,900 €

Accepting the additional costs incurred by a higher pressure drop: = − 33,800 €

Within the period under review, a total cost advantage of = + 51,100 € is thus obtained.

An estimate, plus a cost comparison, must be performed individually for each system in question. Note that further deleterious aspects have not yet been taken into account here, particularly the irreversible degradation of the gas turbine due to fouling. In spite of regular washing routines, the original performance level is impossible to reach again. With three-stage filtration, this effect is almost entirely avoided. Nor have the costs for cleaning agents and their disposal been factored into this computation. Effects improving the overall result, such as its no longer being necessary to add to the running time equivalent operating hours for the start-up procedures required after washing, and the increase in the gas turbine’s availability levels, have likewise not yet been factored in.

Typical Example of Two-stage Filtration in HEPA Quality

System type 2 x Alstom GT13E2
Place of installation South East Asia
Systems rated at 165 MW each
Total volume flow
per system 1,500,000 m³/h
1st filter stage 360 x F8 MaxiPleat MX 95
2nd filter stage 360 x H11 MaxiPleat MX100

Summary and Outlook

The empirical feedback and the results presented demonstrate that installing upgraded filtration quality in the air intake systems for gas turbines definitely makes sense, with concomitant benefits for the users concerned.

By means of systematically analysed feedback from actual applications, characteristic pressure-drop values can be computed for existing filter systems, which permit adequate comparisons with planned modifications towards upgraded filtration quality. Upgrades to three-stage filter systems already implemented with high-efficiency filter elements in the final stage of filtration enable frequent compressor-stage washing routines to be dispensed with. Note that modularized filter systems, which can be installed upstream without any structural modifications and substantially increase filtration quality while only requiring very little additional outlay, have proved their worth in actual operation. Obviating the need for compressor-stage washing, and increased system availability, usually compensate many times over for the slightly higher pressure drop in the upgraded filtration system. Trials in actual practice with two-stage intake air systems that reach a filtration quality equivalent to that of HEPA filters are currently in the test phase and may well prove to be a further step towards optimization, targeting maximally cost-efficient system operation. The option for doing without a washing system opens up yet another step towards cost optimization for turbine manufacturers.

References